

# LATEST RESULTS ON PION RARE DECAYS

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1. the PIBETA experiment: motivation
2. experimental method
3. results from the 1999–2001 run
  - $\pi^+ \rightarrow \pi^0 e^+ \nu$
  - $\pi^+ \rightarrow e^+ \nu \gamma$
4. plans

Sub-Z Workshop  
FNAL, 11-13 May 2004

## *PIBETA Experiment: MOTIVATION and GOALS*

Provide precision tests of Standard Model and QCD predictions:

- $\pi^+ \rightarrow \pi^0 e^+ \nu_e$  – main goal
  - SM tests from CKM unitarity
- $\pi^+ \rightarrow e^+ \nu_e \gamma$  ( $ee$ )
  - $F_A/F_V$ ,  $\pi$  polarizability ( $\chi$ PT prediction)
  - tensor coupling besides  $V - A$  (?)
- $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \gamma$  ( $ee$ )
  - departures from  $V - A$  in  $\mathcal{L}_{\text{weak}}$
- $\pi^+ \rightarrow e^+ \nu_e$  – 2nd phase
  - $e$ - $\mu$  universality
  - pseudoscalar coupling besides  $V - A$
  - massive neutrino, Majoran, ...

## *Recent calculations of pion beta decay radiative corrections*

(1) In the light-front quark model

W. Jaus, Phys. Rev. D **63** (2001) 053009.

- total RC for pion beta decay:  $\delta = (3.230 \pm 0.002) \times 10^{-2}$ .

(2) In chiral perturbation theory

Cirigliano, Knecht, Neufeld and Pichl, Eur. Phys. J. C **27** (2003) 255.

- $\chi$ PT with e-m terms up to  $\mathcal{O}(e^2 p^2)$
- theoretical uncertainty of  $5 \times 10^{-4}$  in extracting  $|V_{ud}|$  from  $\text{BR}(\pi_{e3(\gamma)})$ .

V. A. Baranov,<sup>c</sup> W. Bertl,<sup>b</sup> M. Bychkov,<sup>a</sup> M. V. Chizhov<sup>h</sup>, E. Frlež,<sup>a,\*</sup>  
 N. V. Khomutov,<sup>c</sup> A. S. Korenchenko,<sup>c</sup> S. M. Korenchenko,<sup>c</sup> M. Korolija,<sup>g</sup>  
 T. Kozłowski,<sup>d</sup> N. P. Kravchuk,<sup>c</sup> N. A. Kuchinsky,<sup>c</sup> W. Li,<sup>a</sup> R. C. Minehart,<sup>a</sup>  
 D. Mzhavia,<sup>c,e,\*</sup> D. Počanić,<sup>a,\*</sup> B. G. Ritchie,<sup>f</sup> P. Robmann,<sup>i</sup>  
 A. M. Rozhdestvensky,<sup>c</sup> T. Sakhelashvili,<sup>b</sup> V. V. Sidorkin,<sup>c</sup> L. C. Smith,<sup>a</sup>  
 U. Straumann,<sup>i</sup> I. Supek,<sup>g</sup> P. Truöl,<sup>i</sup> Z. Tsamalaidze,<sup>e</sup> A. van der Schaaf,<sup>i</sup>  
 B. A. VanDevender,<sup>a</sup> E. P. Velicheva,<sup>c</sup> and Y. Wang<sup>a</sup>

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<sup>c</sup>*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*

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<sup>e</sup>*IHEP, Tbilisi, State University, GUS-380086 Tbilisi, Georgia*

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<sup>g</sup>*Rudjer Bošković Institute, HR-10000 Zagreb, Croatia*

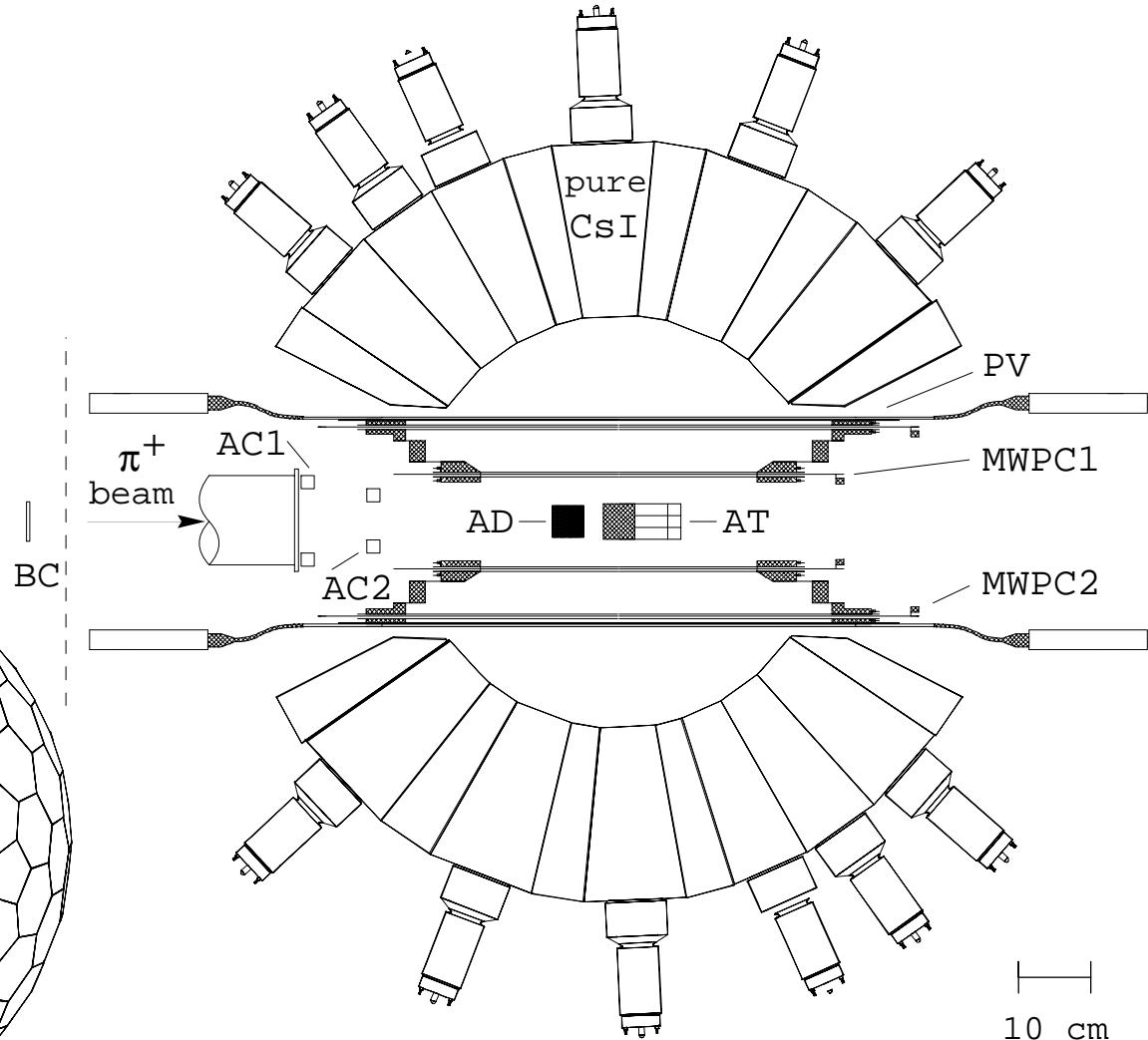
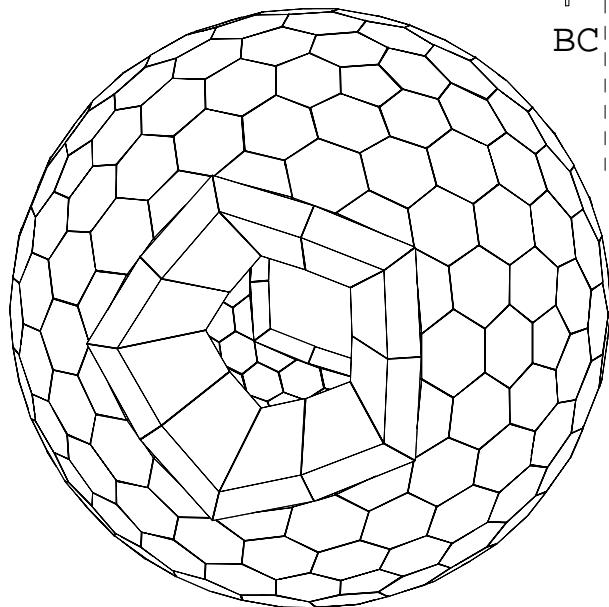
<sup>h</sup>*CSRT, Faculty of Physics, University of Sofia, 1164 Sofia, Bulgaria*

<sup>i</sup>*Physik Institut der Universität Zürich, CH-8057 Zürich, Switzerland*

## *Experimental Method*

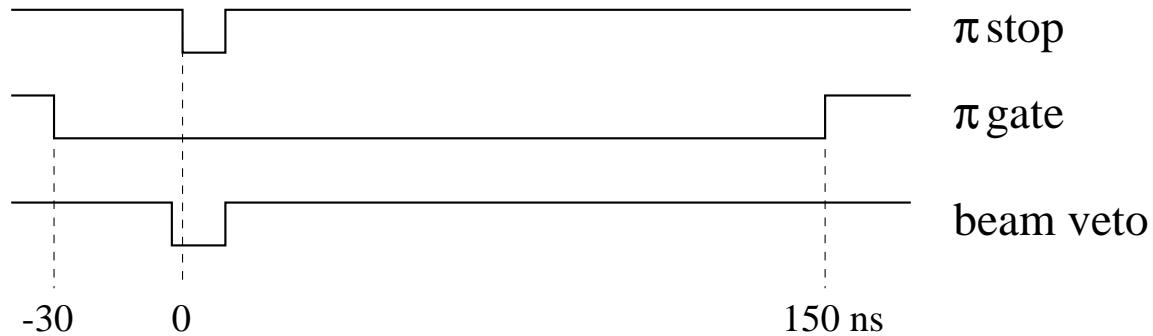
## The PIBETA Experiment:

- stopped  $\pi^+$  beam
- segmented active tgt.
- 240-det. CsI(p) calo.
- central tracking
- digitized PMT signals
- stable temp./humidity
- cosmic  $\mu$  antihouse



## *Experimental Method: Summary*

- Detect  $\pi^+$  decays at rest (during a delayed 180 ns gate).

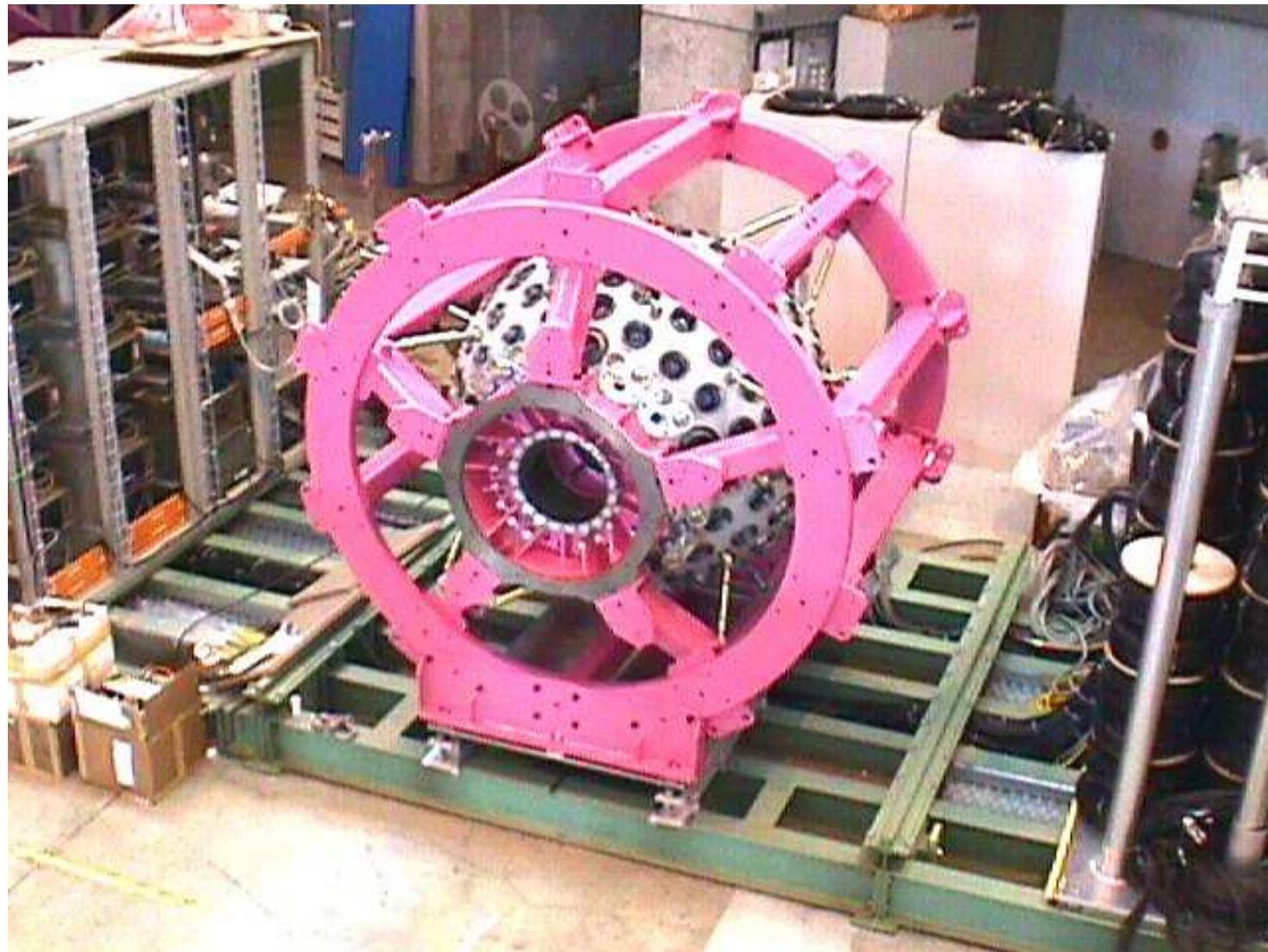


- Use  $\pi^+ \rightarrow e^+ \nu$  prescaled for normalization.
- Accept every  $\pi\beta$  trigger – unbiased ( $\gamma\gamma$  coincidences above Michel endpoint)

$$R_{\pi\beta} = \frac{R_{e\nu} f_{\text{presc}}}{R_{\pi^0 \rightarrow \gamma\gamma}} \cdot \frac{A_{e\nu}}{A_{\pi\beta}} \cdot \frac{N_{\pi\beta}}{N_{e\nu}}$$

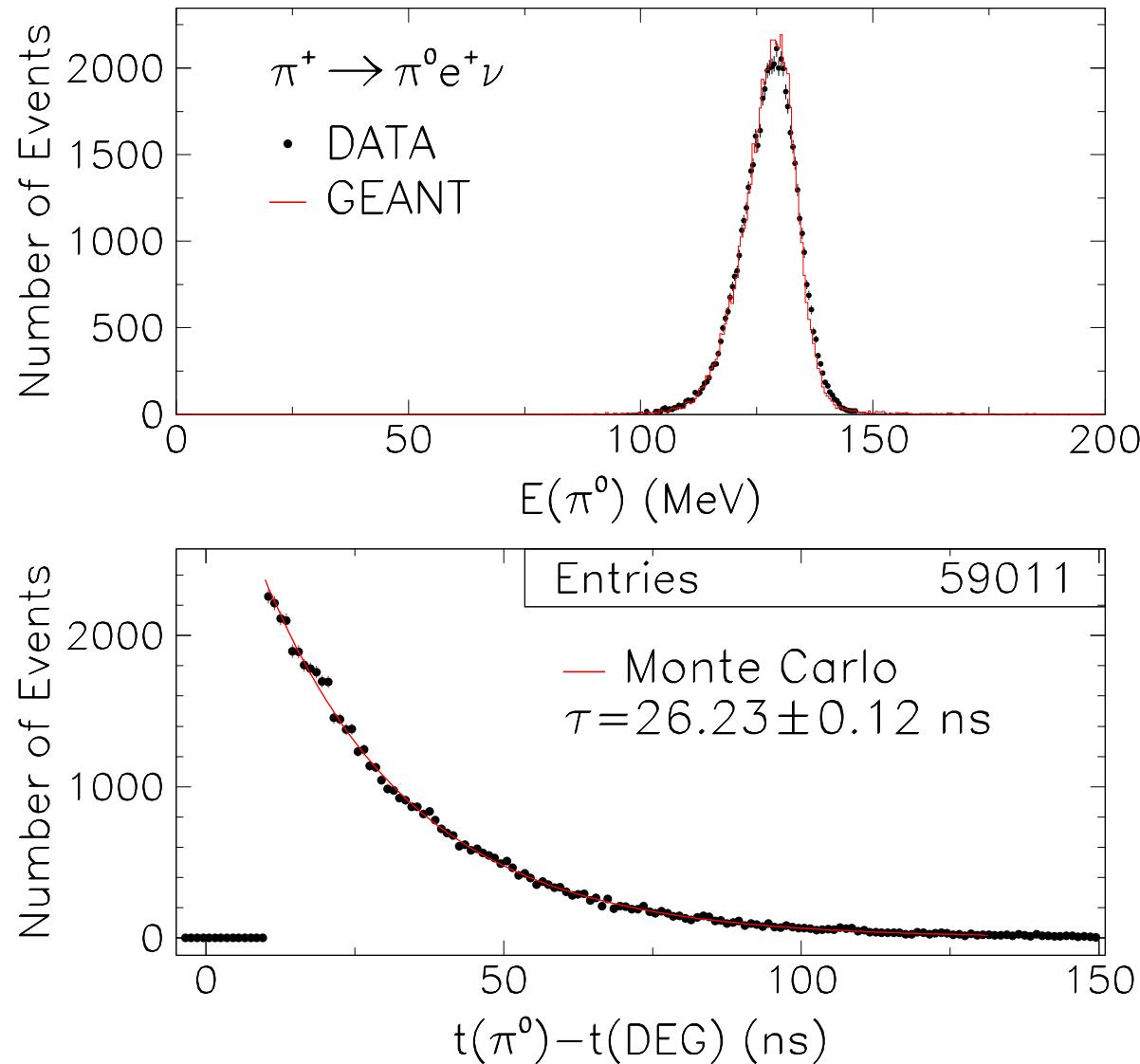
$A_{\pi\beta}$ ,  $A_{e\nu}$  are acceptances for the decay modes, respectively.

## PIBETA Detector Assembly on Platform (1998)

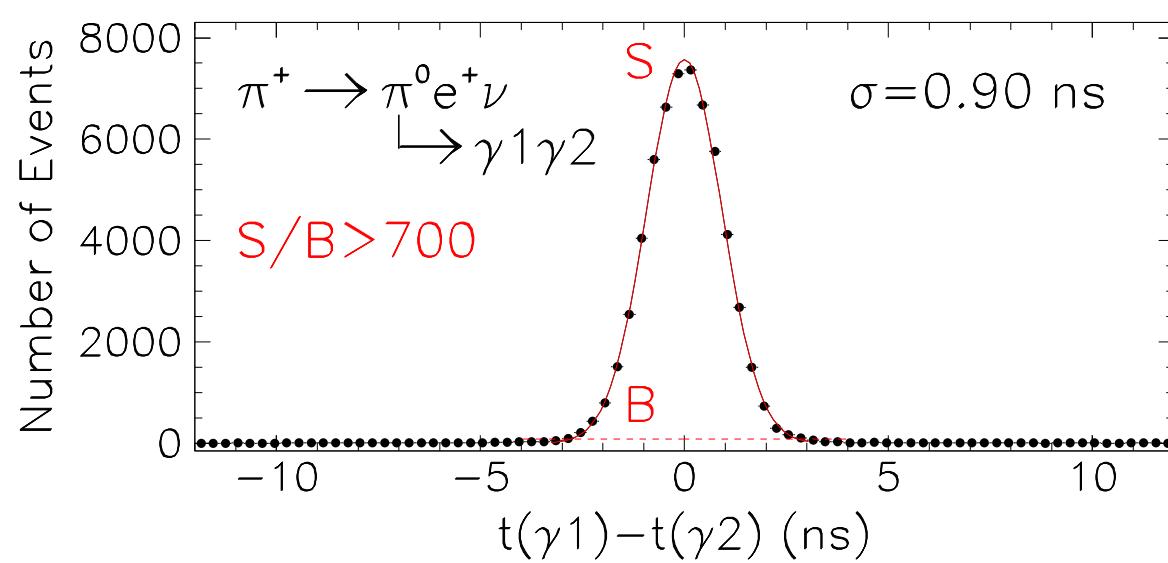
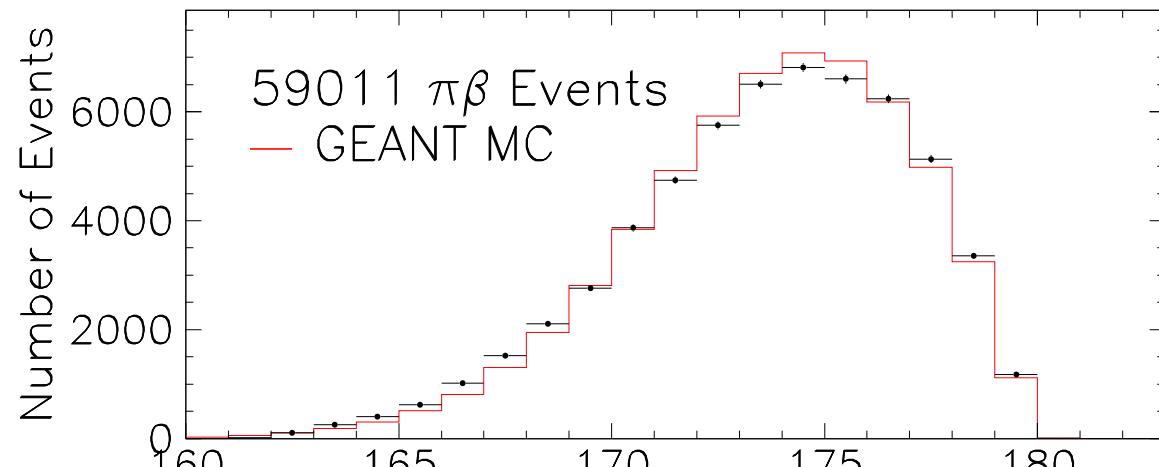


*Results of the 1999–2001 run*

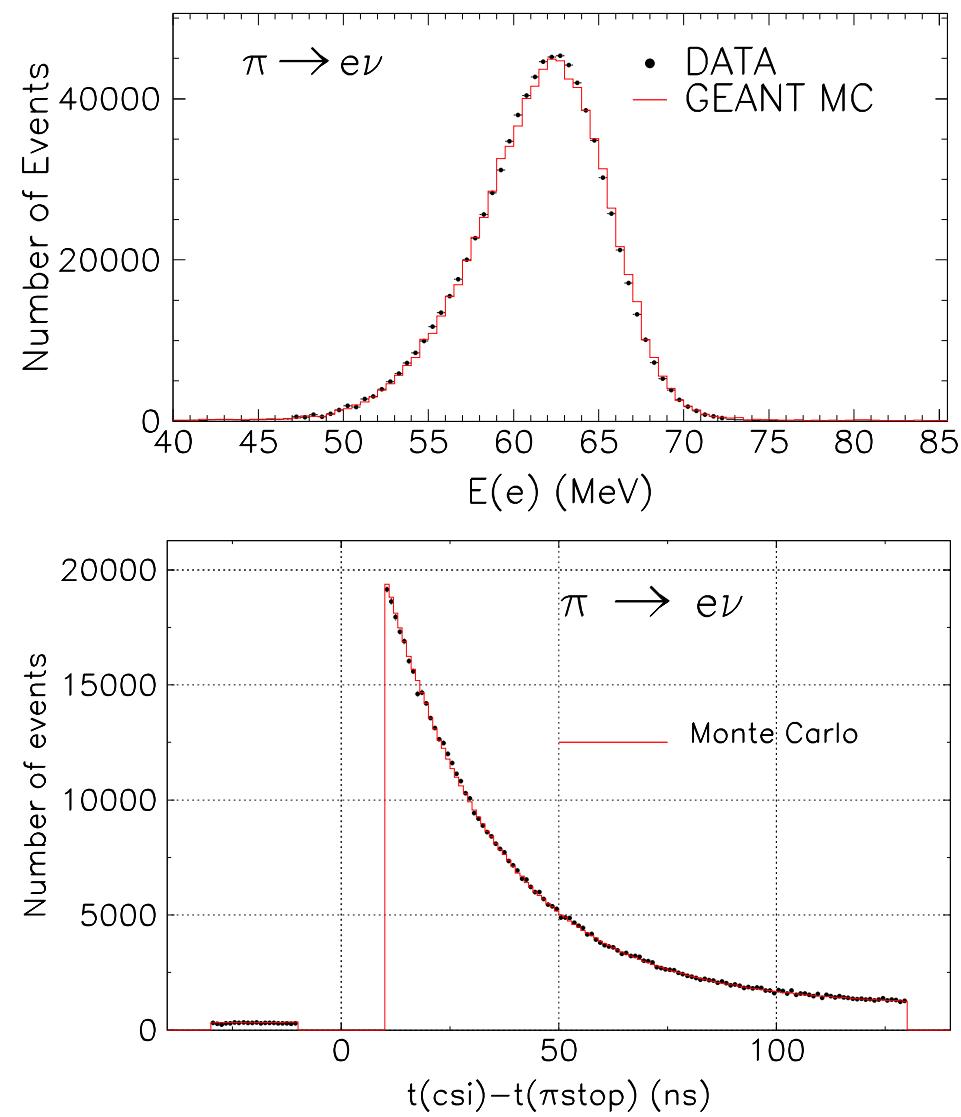
*The  $\pi^+ \rightarrow \pi^0 e^+ \nu$  decay*



$\pi^+ \rightarrow \pi^0 e^+ \nu$  decay cont'd.



*Normalizing decay:*



*Our **Current** Branching Ratio for  $\pi\beta$  Decay*

[arXiv: hep-ex/0312030]

$$R_{\pi\beta}^{\text{exp}} = [1.034 \pm 0.004 \text{ (stat)} \pm 0.007 \text{ (syst)}] \times 10^{-8},$$

McFarlane et al. (PRD 1985):  $R \simeq 1.026 \pm 0.039 \times 10^{-8}$

SM Prediction (PDG, 2002):

$$\begin{aligned} R = & 1.038 - 1.041 \times 10^{-8} \quad (90\% \text{ C.L.}) \\ & (1.005 - 1.008 \times 10^{-8} \quad \text{excl. rad. corr.}) \end{aligned}$$

PDG 2002:  $V_{ud} = 0.9734(8)$

PIBETA current:  $V_{ud} = 0.9716(39).$

## Summary of $\pi\beta$ Uncertainties (%)

	at end of analysis phase:	current	final
external:	pion lifetime	0.019	0.019
	$BR(\pi \rightarrow e\nu)$	0.33	$\sim 0.1^\dagger$
	$BR(\pi^0 \rightarrow \gamma\gamma)$	0.032	0.032
internal:	$A(\pi\beta)/A(e\nu)$	0.6	< 0.3
	$\Delta t(\gamma - e)$	0.03	0.03
	E threshold	< 0.1	< 0.1
statistical:		0.4	$\sim 0.4$
total:		$\sim 0.8$	$\lesssim 0.5$

<sup>†</sup> Requires a new measurement.

$$\pi^+ \rightarrow e^+ \nu \gamma \text{ (S/B)}$$

Region A:

$$E_\gamma, E_{e^+} > 51.7 \text{ MeV}$$

Region B:

$$E_\gamma > 55.6 \text{ MeV}$$

$$E_{e^+} > 20 \text{ MeV}$$

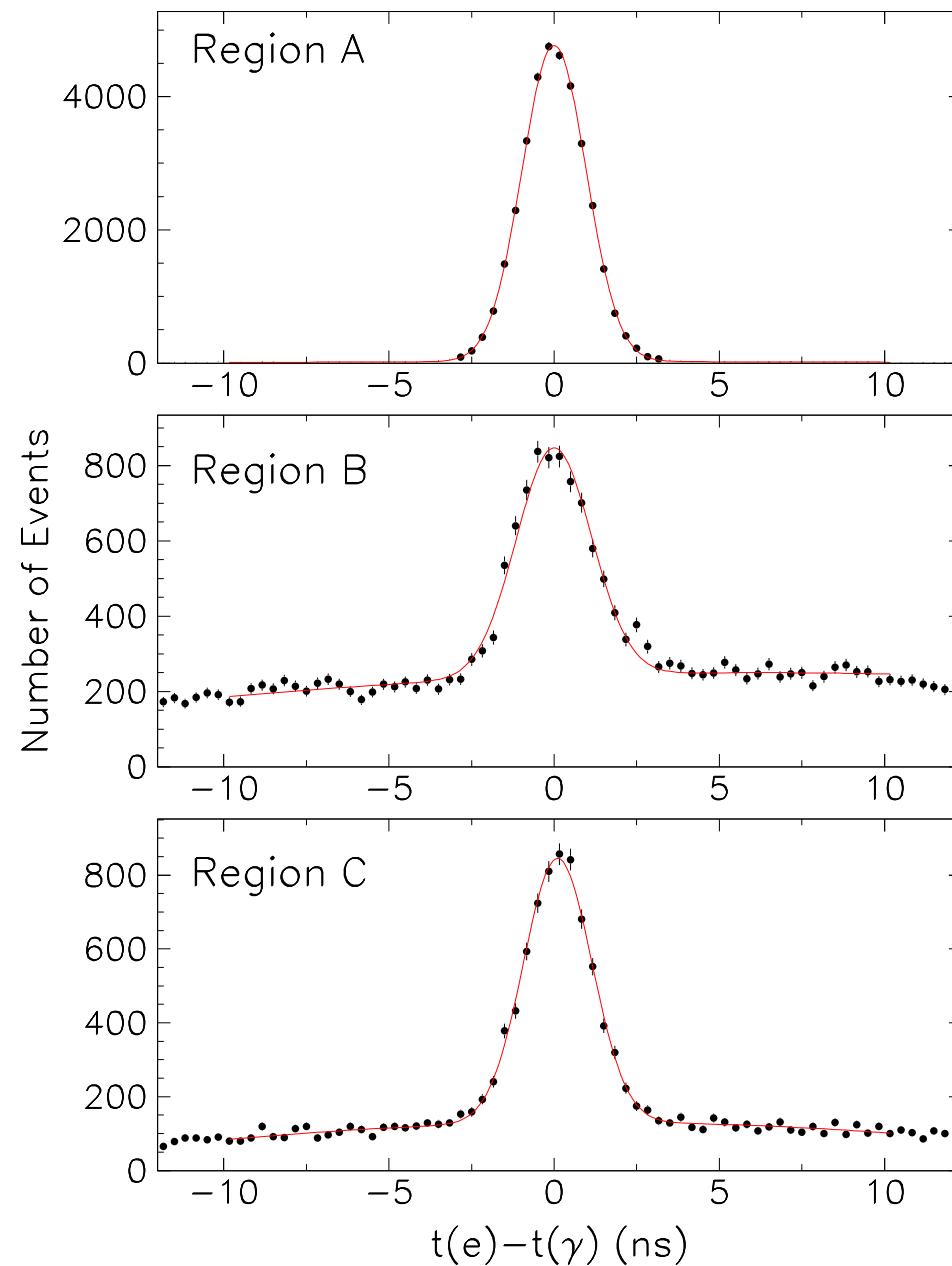
$$\theta_{e\gamma} > 40^\circ$$

Region C:

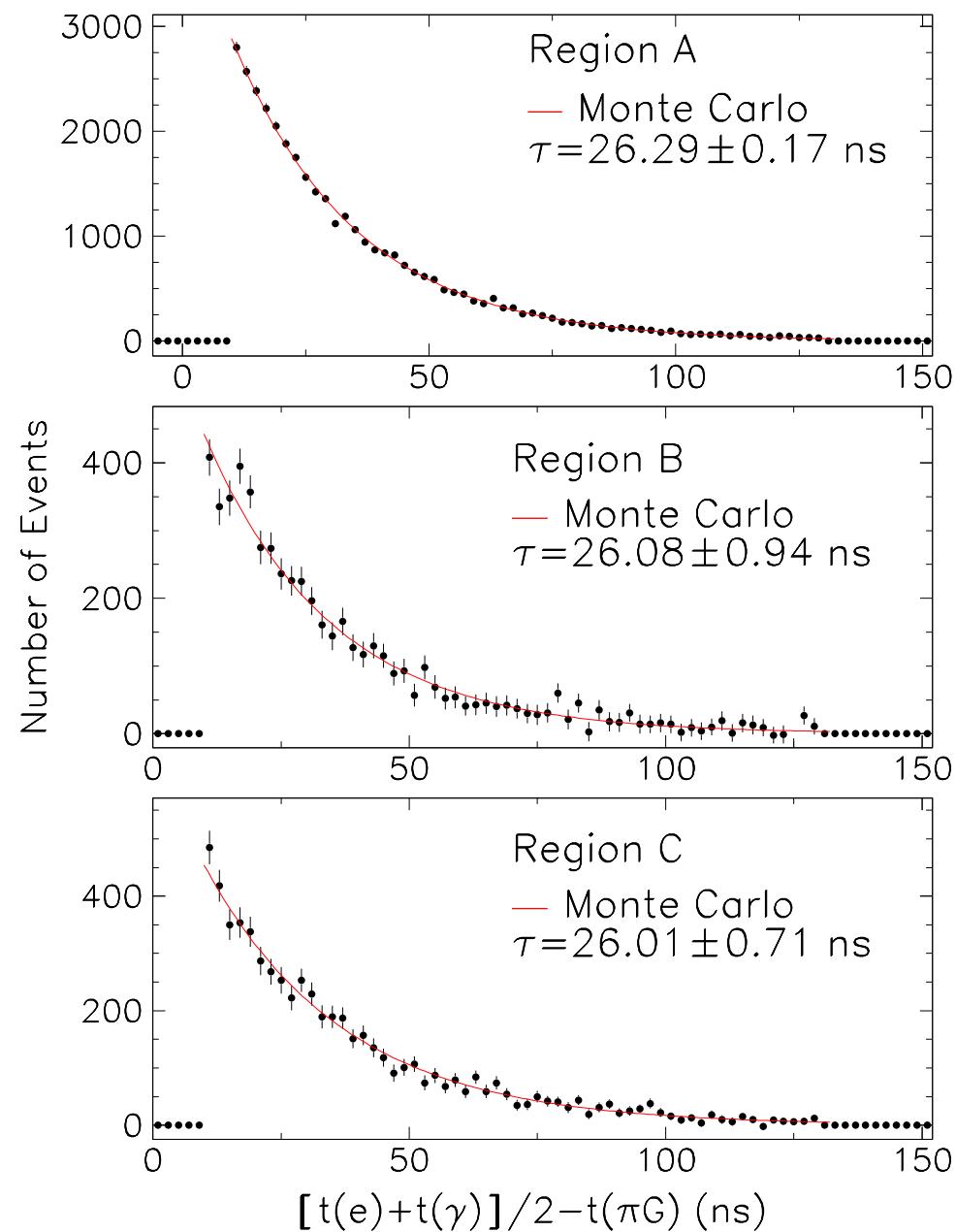
$$E_\gamma > 20 \text{ MeV}$$

$$E_{e^+} > 55.6 \text{ MeV}$$

$$\theta_{e\gamma} > 40^\circ$$



$\pi^+ \rightarrow e^+ \nu \gamma$   
(timing)



$\pi \rightarrow e\nu\gamma$ : *Pion form factors and polarizability in  $\chi$ PT*

To first order in  $\chi$ PT the pion weak form factors and charge radius fix two basic parameters:

$$\frac{1}{6} \langle r_\pi^2 \rangle = \frac{2}{F_\pi^2} \alpha_9^r - \frac{1}{96\pi^2 F_\pi^2} \left( \ln \frac{m_\pi^2}{\mu^2} + \frac{1}{2} \ln \frac{m_K^2}{\mu^2} + \frac{3}{2} \right) ,$$

while

$$\frac{F_A}{F_V} = 32\pi^2 (\alpha_9^r + \alpha_{10}^r) ,$$

while the pion polarizability is given by

$$\alpha_E = \frac{4\alpha}{m_\pi F_\pi^2} (\alpha_9^r + \alpha_{10}^r) ,$$

so that

$$\alpha_E = \frac{\alpha}{8\pi^2 m_\pi F_\pi^2} \cdot \frac{F_A}{F_V} \simeq 6.24 \times 10^{-4} \cdot \frac{F_A}{F_V} .$$

*AVAILABLE DATA on Pion Form Factors*

$$|F_V| \stackrel{\text{cvc}}{=} \frac{1}{\alpha} \sqrt{\frac{2\hbar}{\pi \tau_{\pi^0} m_{\pi^0}}} = 0.0259(5) .$$

$F_A \times 10^4$	reference
106 ± 60	Bolotov et al. (1990)
135 ± 16	Bay et al. (1986)
60 ± 30	Piilonen et al. (1986)
110 ± 30	Stetz et al. (1979)
116 ± 16	world average (PDG 2002)

## *Problems with pion form factors prior to 1999*

A.A. Poblagev found: [PL B238 (1990) 108, PL B286 (1992) 169]

- (a) inconsistencies in data set (part. ISTRA data),
- (b) need to include Tensor  $q-l$  coupling with:  
 $F_T \sim -0.0056 \pm 0.0017$ . (updated recently in several papers)

P. Herczeg: [PRD 49 (1994) 247]

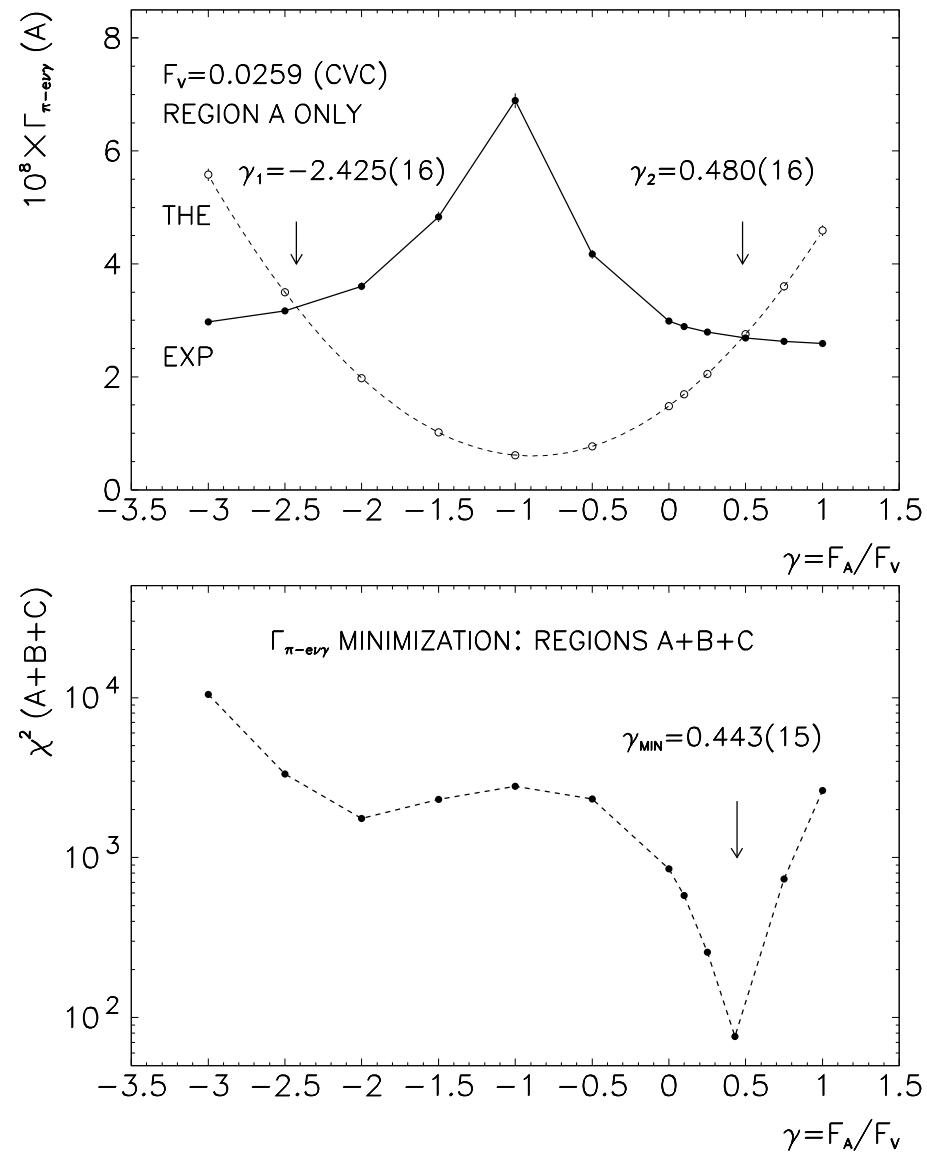
confirmed there is room (barely) for  $F_T$  of this order of magnitude from other weak decay data ( $S = 0$  leptoquarks at tree level?).

M. Chizhov: [Mod. Phys. Lett. A8 (1993) 2753]

proposed a new intermediate chiral boson with anomalous T interaction with matter. (updated recently in several papers)

# Form Factor Fits

$$\pi^+ \rightarrow e^+ \nu \gamma$$



## Results of the SM fit

[arXiv: hep-ex/0312029]

Best-fit  $\pi \rightarrow e\nu\gamma$  branching ratios obtained with:

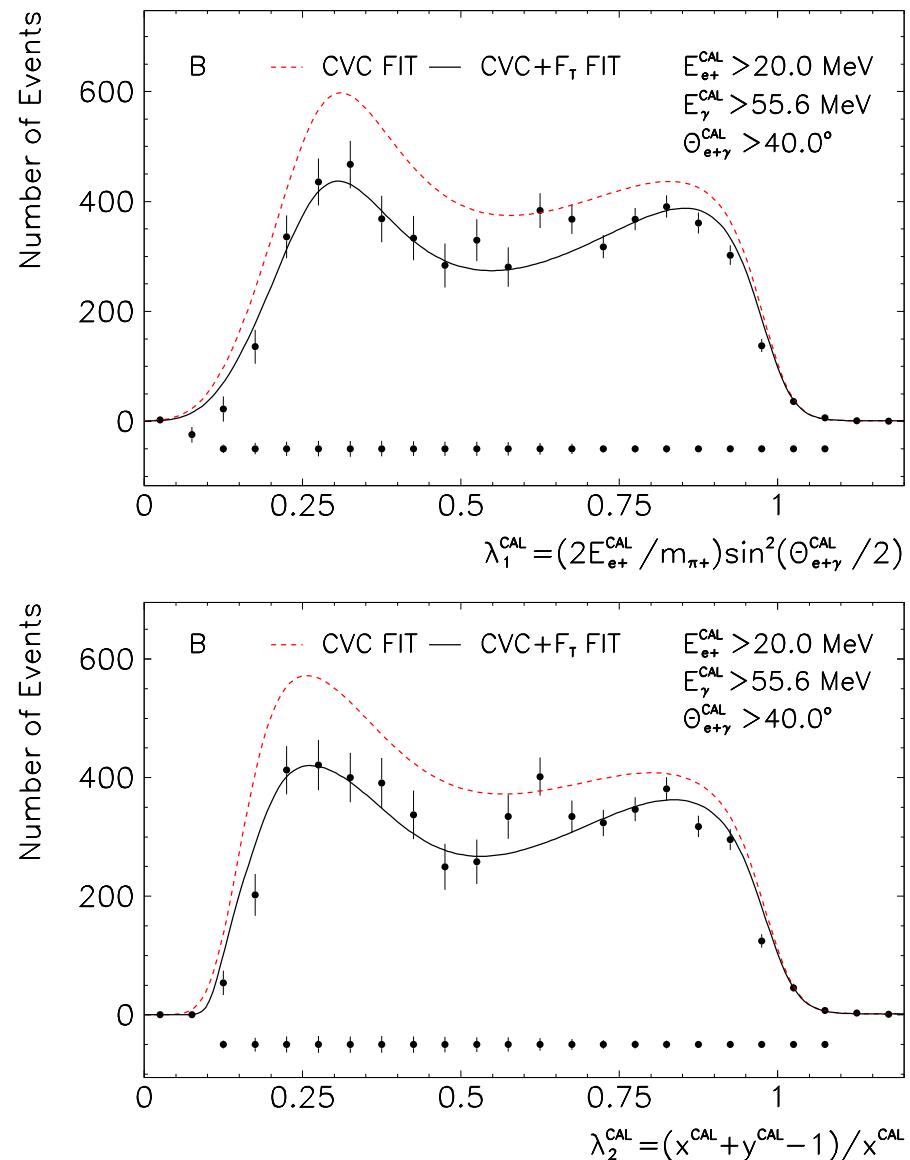
$F_V = 0.0259$  (fixed) and  $F_A = 0.0115(4)$  (fit)

$$\chi^2/\text{d.o.f.} = 25.4.$$

Radiative corrections are included in the calculations.

$E_{e^+}^{\min}$ (MeV)	$E_\gamma^{\min}$ (MeV)	$\theta_{e\gamma}^{\min}$	$R_{\text{exp}}$ ( $\times 10^{-8}$ )	$R_{\text{the}}$ ( $\times 10^{-8}$ )
50	50	—	2.71(5)	2.583(1)
10	50	40°	11.6(3)	14.34(1)
50	10	40°	39.1(13)	37.83(1)

## Region B: global fits



## *Plans for the Future*

- Bring analysis up to the proposed level of uncertainty. ✓
- Run the approved dedicated  $\pi \rightarrow e\nu\gamma$  experiment (R-04-01.1)  
May–Aug 2004
- Prepare new proposal and collaboration for a precise  $\pi \rightarrow e\nu$  measurement.
- We are actively considering a new search for the  $\pi^0 \rightarrow \gamma\gamma\gamma$  decay using the PIBETA apparatus.

<http://pibeta.phys.virginia.edu/>

<http://pibeta.web.psi.ch/>

## STATUS OF CKM UNITARITY

- $|V_{us}| \simeq 0.2196 \pm 0.0026$  from  $K_{e3}$  decays.
- $|V_{ub}| \simeq 0.0036 \pm 0.0007$  from  $B$  decays.
- $|V_{ud}|$  from superallowed Fermi nuclear  $\beta$  decays

Circa 1990 Hardy reconciled Ormand & Brown's and Towner's *ft* values:  
 $V_{ud} = 0.9740(5)$ ; PDG has added a flat uncertainty of 0.0005 due to  
unknown nuclear medium effects on isospin breaking:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9969 \pm 0.0023, \text{ i.e.,}$$

$$\Delta \equiv 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = 0.0031(23) \quad \text{or} \quad 1.5\sigma.$$

Without the PDG add'l error, we would have

$$\Delta = 0.0031(15), \quad \text{or} \quad 2.1\sigma.$$

## STATUS OF CKM UNITARITY (2)

- $|V_{us}| \simeq 0.2196 \pm 0.0026$  from  $K_{e3}$  decays.
- $|V_{ub}| \simeq 0.0036 \pm 0.0007$  from  $B$  decays.
- $|V_{ud}|$  from neutron  $\beta$  decay

García, García-Luna and López Castro [Phys. Lett. **B500** (2001) 66] found:

$$V_{ud} = 0.9717(20) \quad \Delta = .0072(31) \quad \text{data set 'R'}$$

$$0.9790(17) \quad -0.0066(35) \quad \text{data set 'LYB'}$$

Meanwhile, PDG 2000 world average was:

$$|V_{ud}| = 0.9728(12) \quad \Rightarrow \quad \Delta = 0.0054(26), \quad \text{or} \quad 2\sigma$$

However, in May 2002 PERKEO II published new results:

$$|V_{ud}| = 0.9713(13) \quad \Rightarrow \quad \Delta = 0.0083(28), \quad \text{or} \quad 3\sigma.$$

## STATUS OF CKM UNITARITY (3)

BNL E865 recently reported a  $2.3\sigma$  higher value for  $K_{e3}^+$  decay BR, and, hence, for  $|V_{us}|^2$  [A. Sher et al. hep-ph/0305042]:

$$V_{us} = 0.2272 \pm 0.0023_{\text{rate}} \pm 0.0007_{\lambda+} \pm 0.0018_{f+} = 0.2272(30)$$

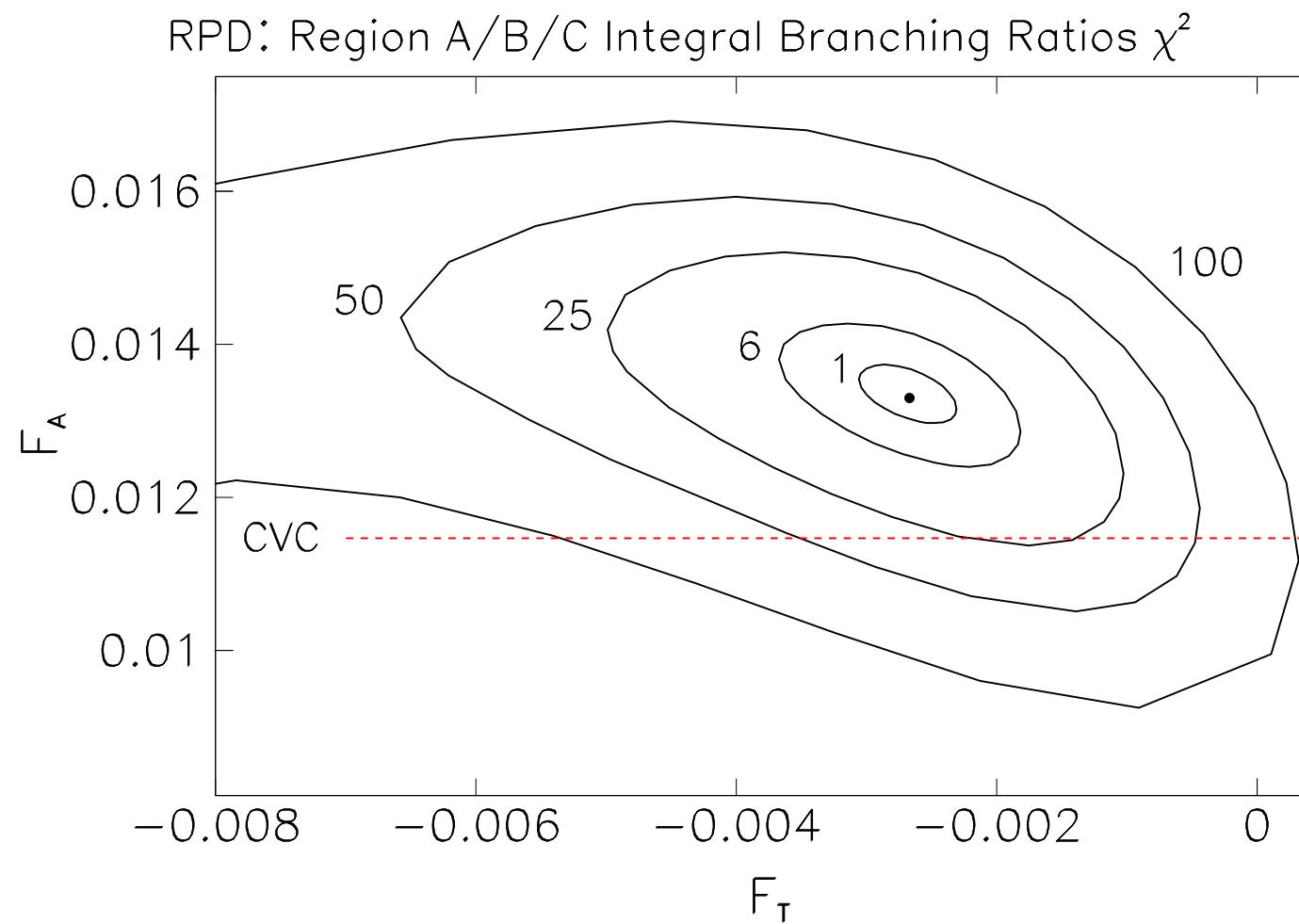
If we take  $\begin{cases} |V_{ud}| = 0.9740(23) & \text{from SFT in nuclei, and} \\ |V_{ub}| = 0.0036(7) & \text{from } B \text{ decays} \end{cases}$

we get:  $\Delta = -0.0003 \pm 0.0024$ .

Furthermore, Cabibbo, Swallow and Winston [hep-ph/0307214] used a new technique to reanalyze hyperon semileptonic decay data and obtained:

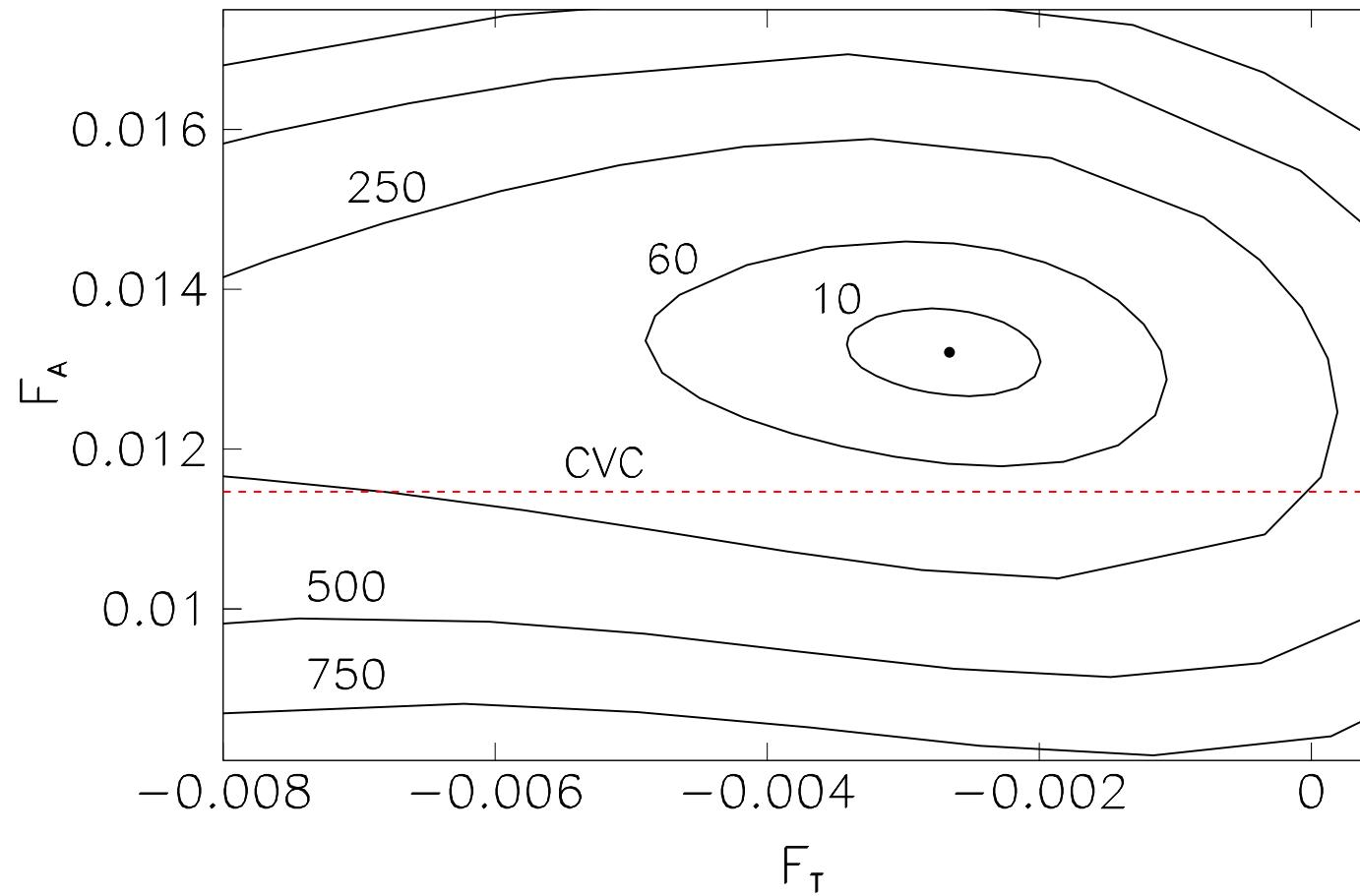
$$V_{us} = 0.2250(27) \quad \Rightarrow \quad \Delta = 0.0007(23) .$$

## Global Fits with $F_T$ : integral

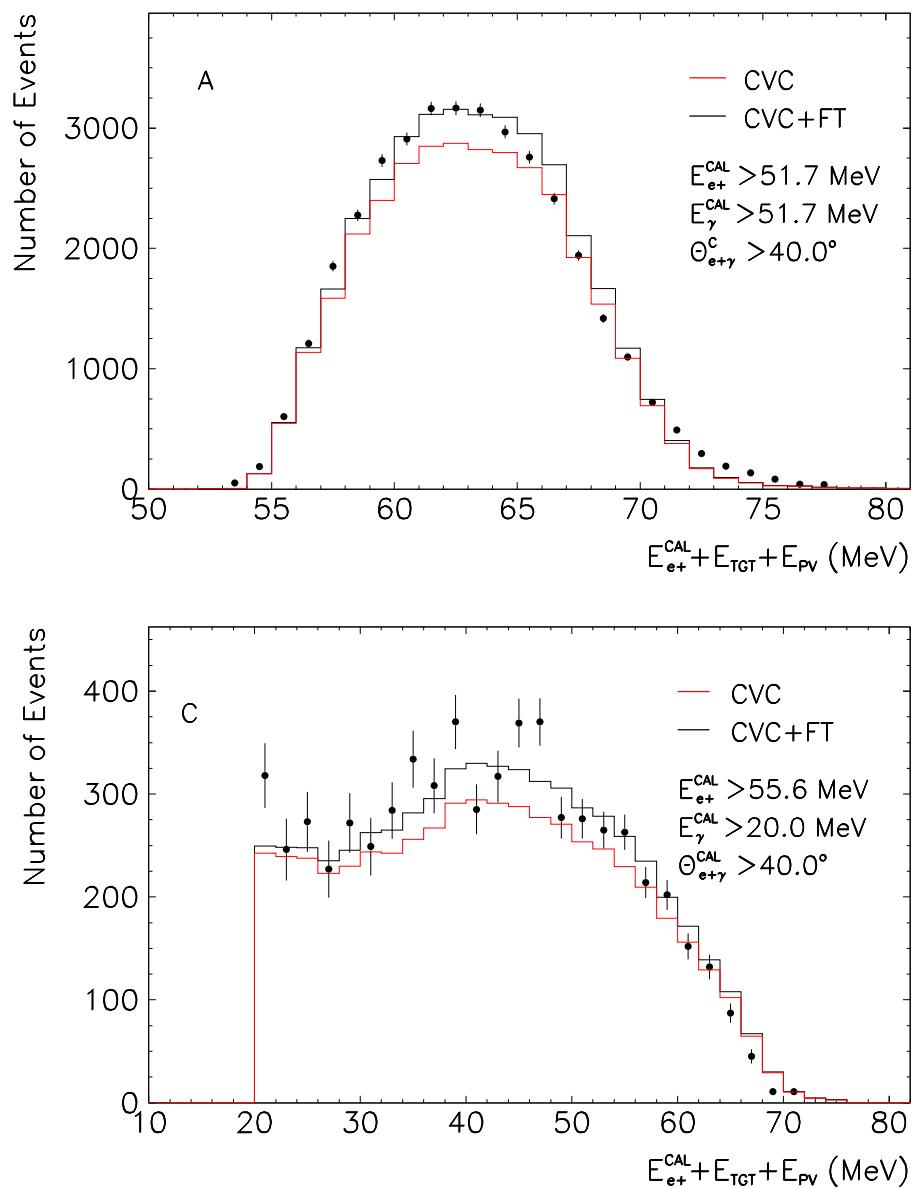


## Global Fits with $F_T$ : differential

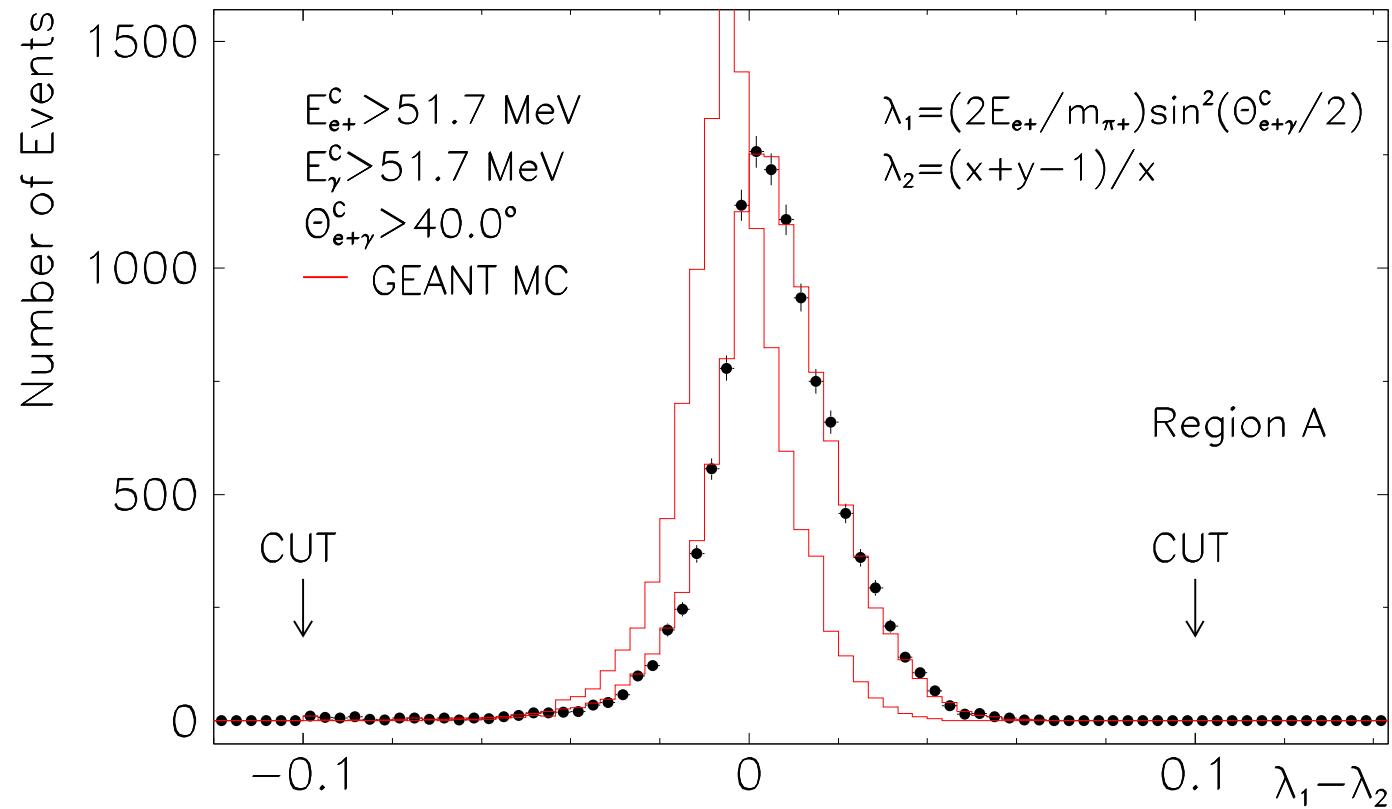
RPD: Absolute Differential Branching Ratios  $\chi^2$  (ndf=174)



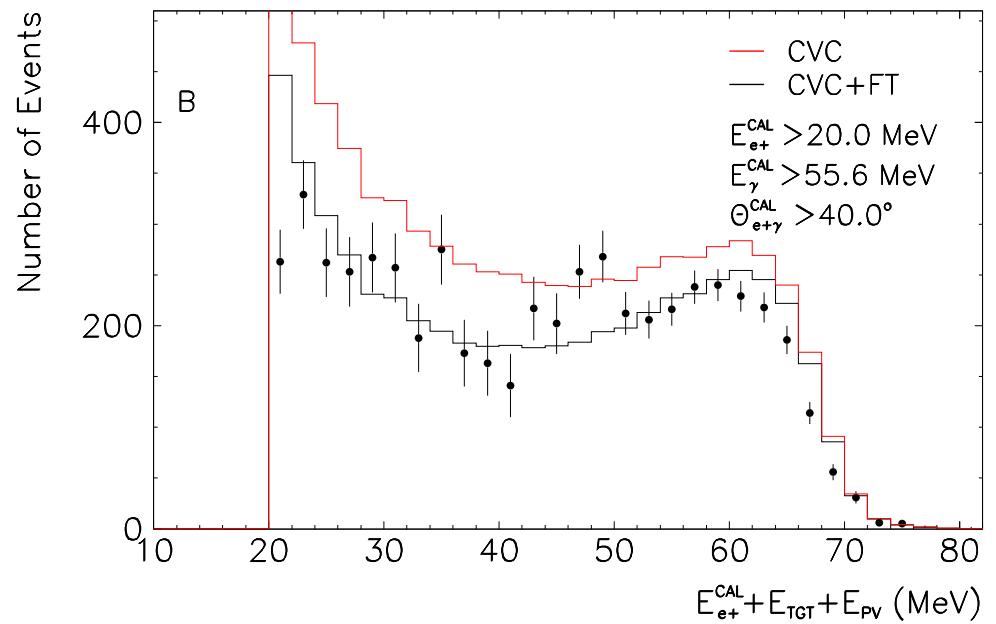
## Sensitivity of regions A and C



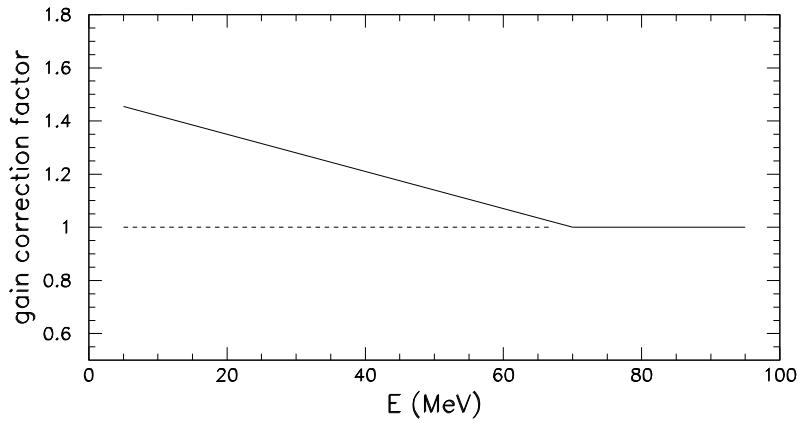
### Checking energy calibration: $\lambda_1 - \lambda_2$ :



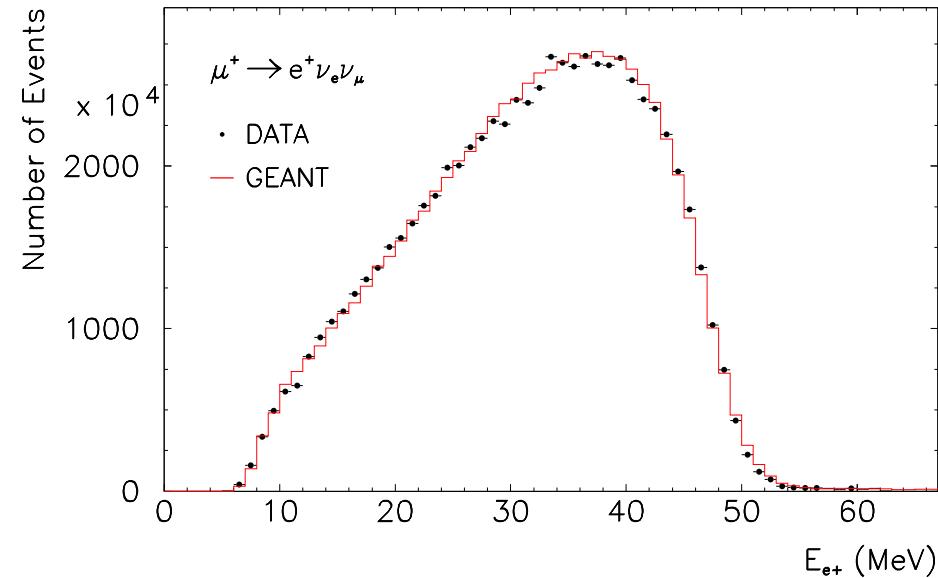
Checking energy calibration;  
 $e^+$  energy loss – gain shift:



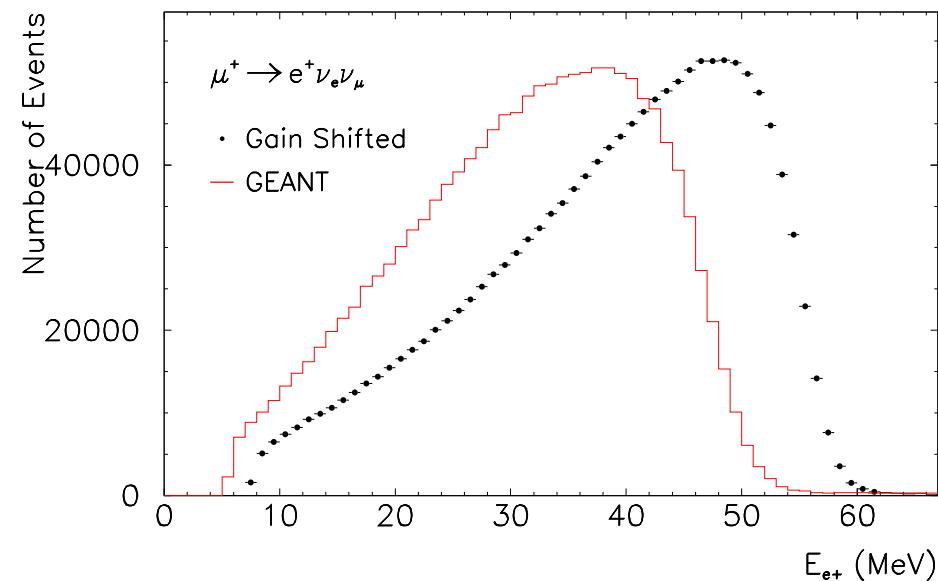
gain correction needed to  
match SM integral:



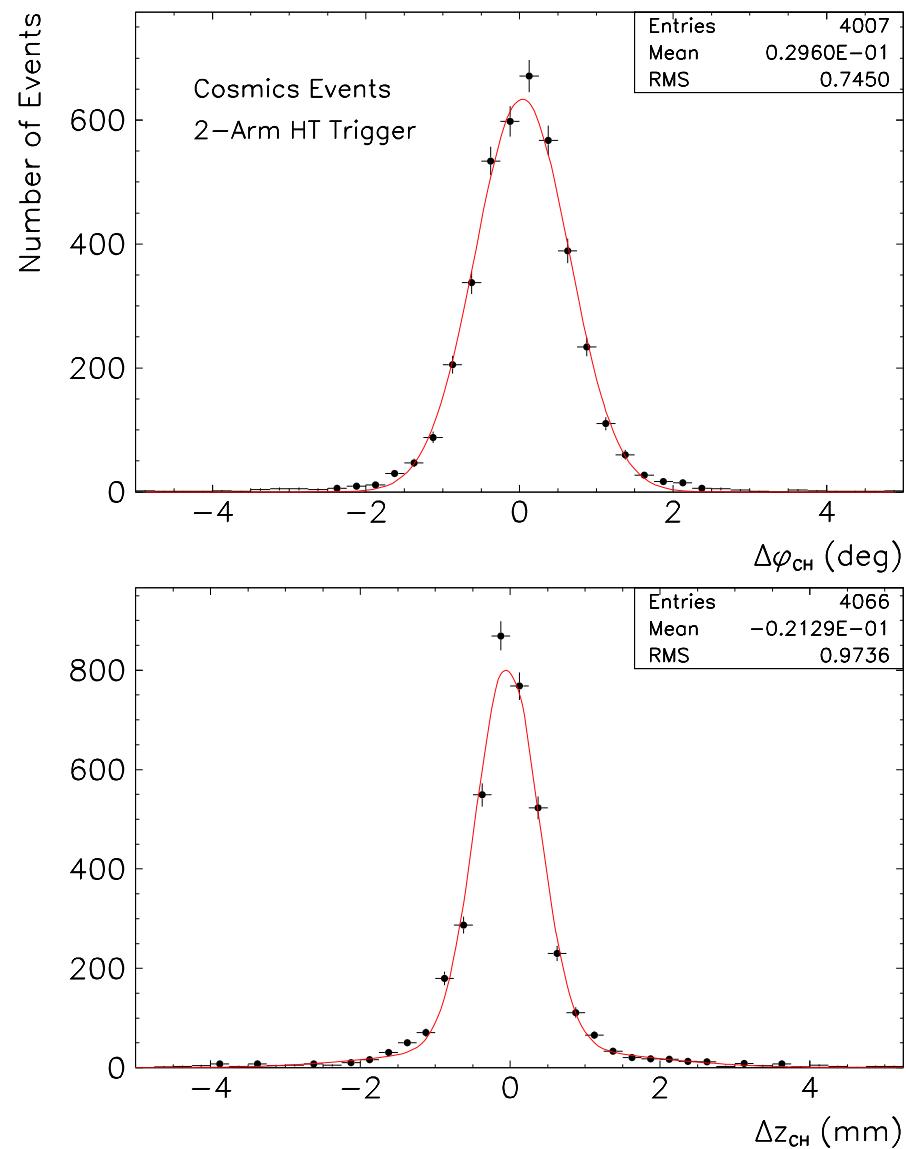
Checking energy calibration;  
 $e^+$  energy loss – gain shift:



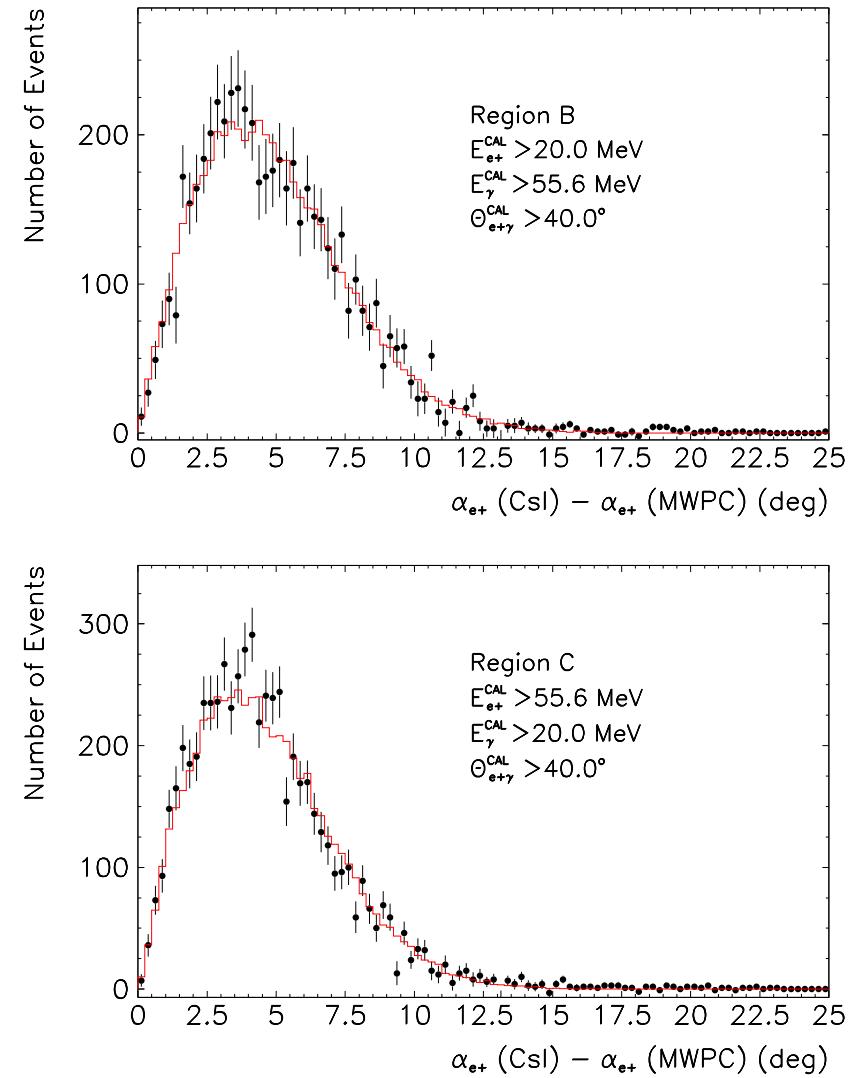
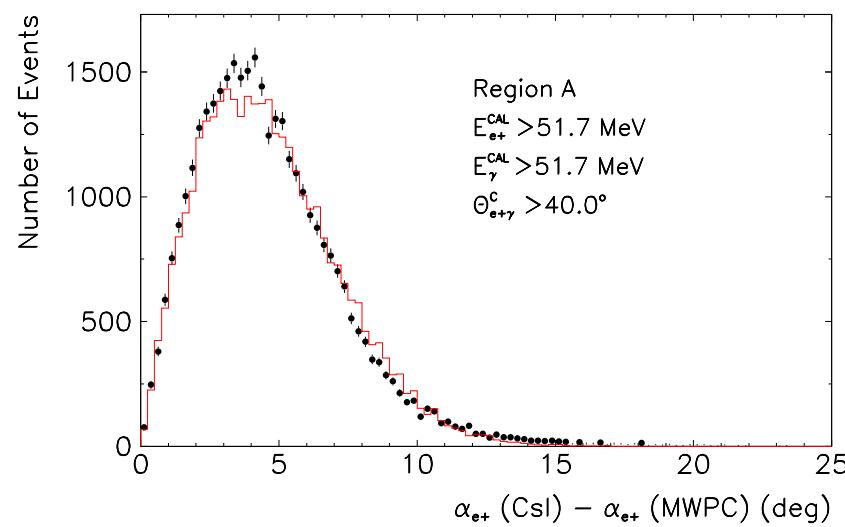
gain-shifted Michel spectrum:



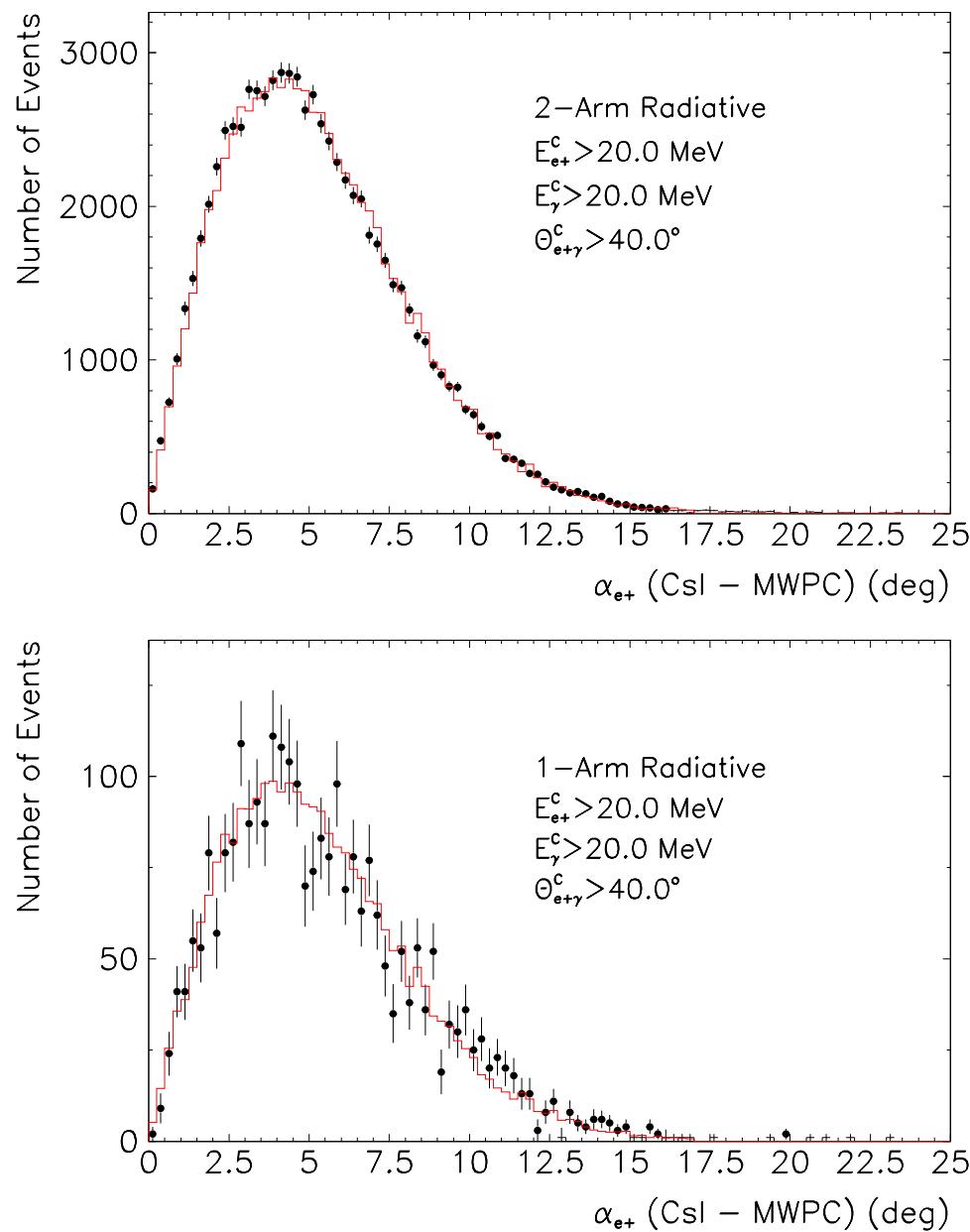
A look at chamber tracking resolution:



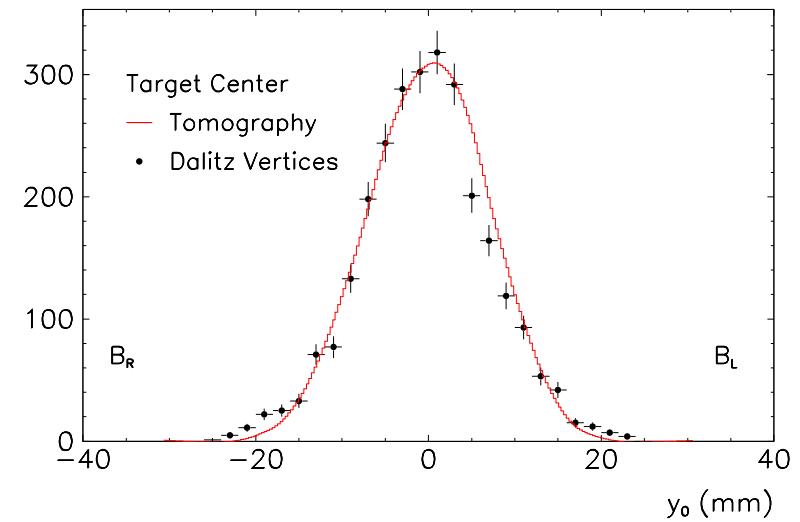
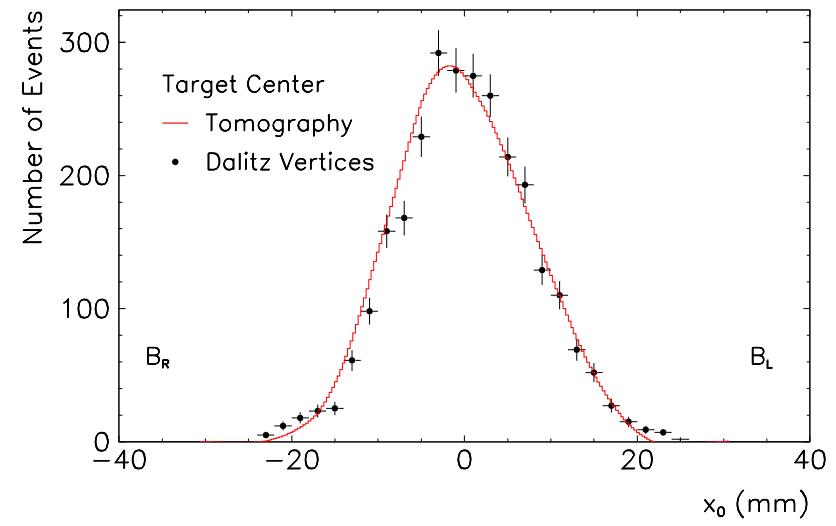
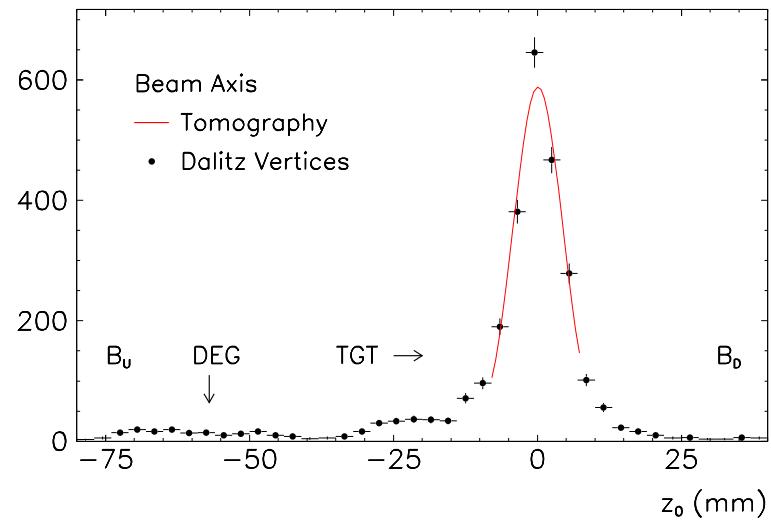
## Difference between MWPC and calorimeter tracks:



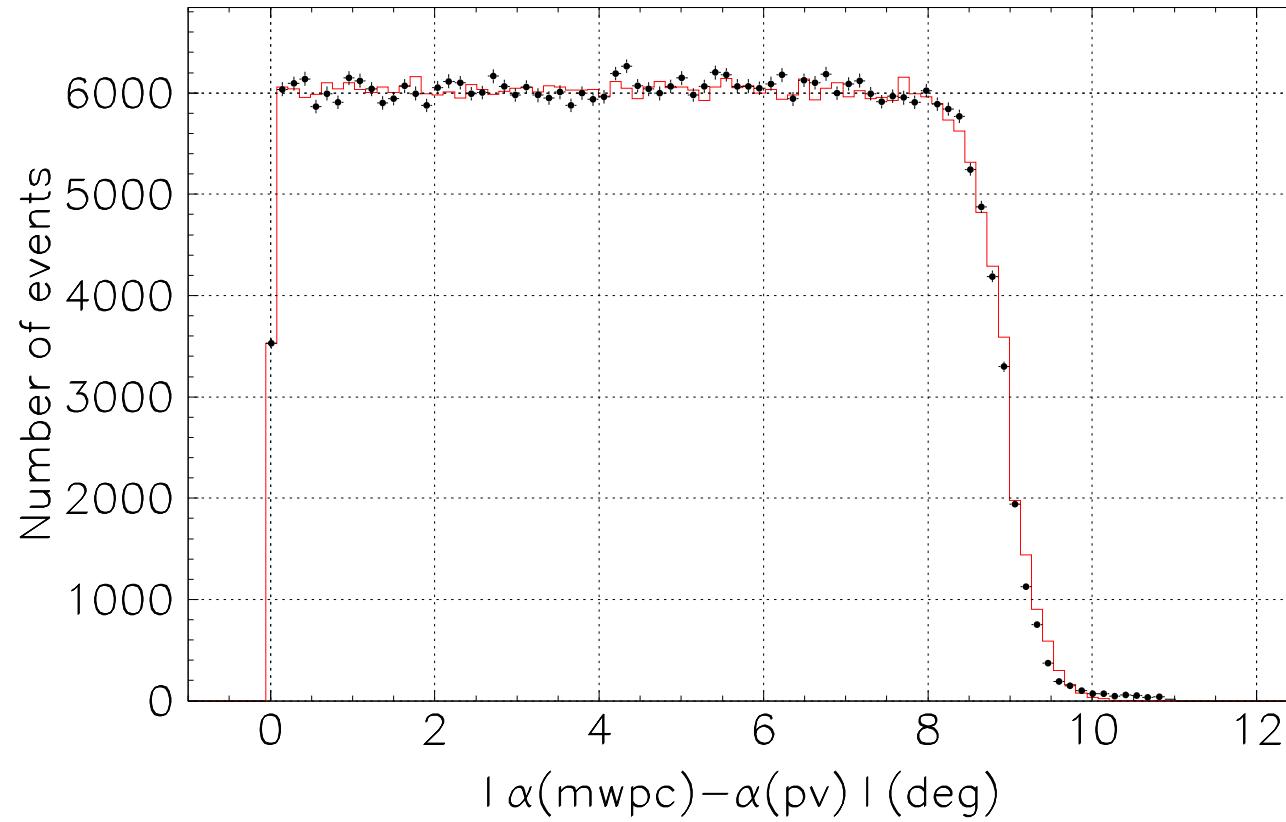
## Radiative muon decay tracking:



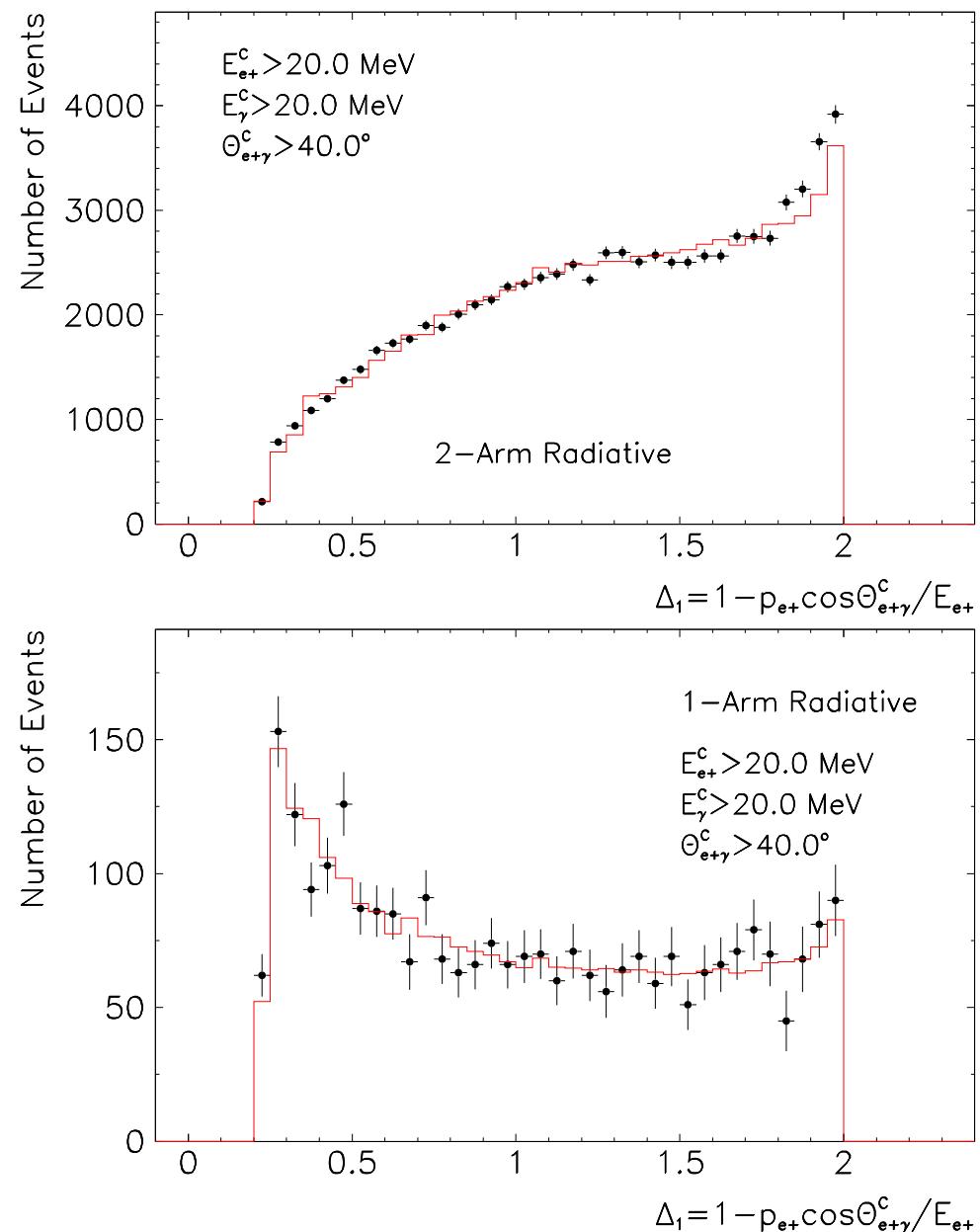
## Backtracking Dalitz decays compared with beam tomography



$\pi \rightarrow e\nu$  tracking of the Plastic Veto bars



## More on Radiative Muon Decays



## *Details of the 2004 run*

Run for 15 weeks in  $\pi E1$  beam area, starting in May 2004.

Optimize for 1-arm triggers at  $\sim 100 - 200 \text{ k } \pi_{\text{stop}}/\text{s}$ .

Simplified one-piece target .

- Counting statistics in the first phase:

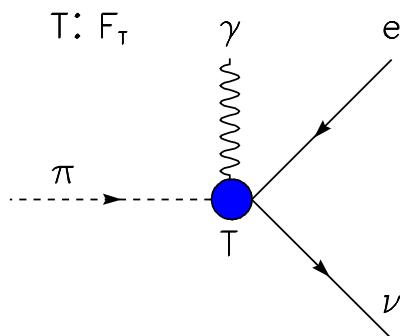
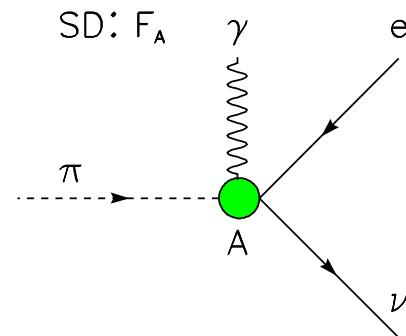
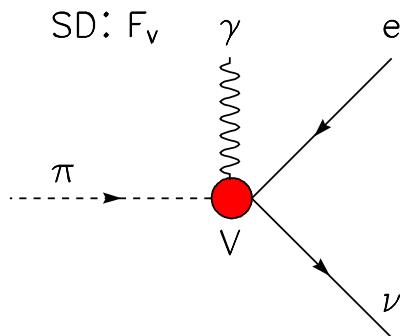
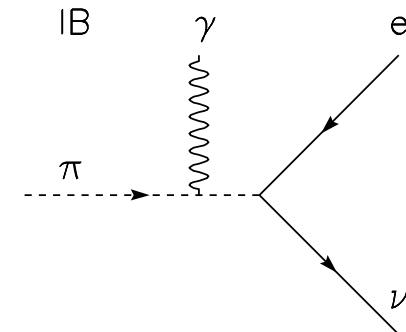
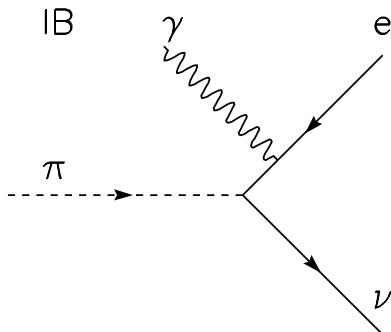
$$N_A : (N_B + N_C) = 31 \text{ k} : 12 \text{ k}$$

proposed run: add another  $\sim 20 \text{ k}$  in B, C, and  $\sim 3 \text{ k}$  in A.

- New data will have  $S/B > 40!$
- This will enable us to extend the usable phase space down to  $\sim 10 \text{ MeV}$  in  $E_e$ ,  $E_\gamma$ , and  $\theta_{e\gamma}$  down to  $\sim 30^\circ$ .
- We'll add  $\sim 300 \text{ k}$  high-quality muon radiative events; important as a cross-check.
- We'll add  $\sim 5 \text{ k}$  high-quality pion beta decay events.

$$\pi^+ \rightarrow e^+ \nu \gamma:$$

*Is there anything  
else besides V-A  
in RPD?*



Exchange of S=0 leptoquarks

P Herczeg, PRD 49 (1994) 247

*The  $\pi \rightarrow e\nu\gamma$  amplitude and BR*

The IB amplitude:

$$M_{IB} = -i \frac{eG_F V_{ud}}{\sqrt{2}} f_\pi m_e \epsilon^{\mu*} \bar{e} \left( \frac{k_\mu}{kq} - \frac{p_\mu}{pq} + \frac{\sigma_{\mu\nu} q^\nu}{2kq} \right) \times (1 - \gamma_5) \nu .$$

The structure-dependent amplitude:

$$M_{SD} = \frac{eG_F V_{ud}}{m_\pi \sqrt{2}} \epsilon^{\nu*} \bar{e} \gamma^\mu (1 - \gamma_5) \nu \times [\textcolor{red}{F_V} \epsilon_{\mu\nu\sigma\tau} p^\sigma q^\tau + i \textcolor{red}{F_A} (g_{\mu\nu} pq - p_\nu q_\mu)] .$$

The SM branching ratio ( $\gamma \equiv F_A/F_V$ )

$$\begin{aligned} \frac{d\Gamma_{\pi e 2\gamma}}{dx dy} = & \frac{\alpha}{2\pi} \Gamma_{\pi e 2} \left\{ IB(x, y) + \left( \frac{\textcolor{red}{F_V} m_\pi^2}{2f_\pi m_e} \right)^2 \right. \\ & \times \left[ (1 + \gamma)^2 SD^+(x, y) + (1 - \gamma)^2 SD^-(x, y) \right] \\ & \left. + \left( \frac{\textcolor{red}{F_V} m_\pi}{f_\pi} \right) [(1 + \gamma) S_{\text{int}}^+(x, y) + (1 - \gamma) S_{\text{int}}^-(x, y)] \right\} . \end{aligned}$$